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Our long-term goal is to develop both a coupled ocean-atmosphere model and a statistical forecasting model that have significant and quantified skill in predicting the evolution of Madden-Julian Oscillations (MJO's), which is highly relevant to ONR long-term objectives. This requires developing a better understanding of the sensitivities of the atmospheric circulation associated with MJO's to small-scale SST anomalies, regional-scale SST anomalies, the diurnal cycle, surface waves, upper-ocean mixing, and various other aspects of ocean-atmosphere feedbacks.

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Predictability and Coupled Dynamics of MJO During DYNAMO

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LONG-TERM GOALS

Our long-term goal is to develop both a coupled ocean-atmosphere model and a statistical forecasting model that have significant and quantified skill in predicting the evolution of Madden-Julian Oscillations (MJO's), which is highly relevant to ONR long-term objectives. This requires developing a better understanding of the sensitivities of the atmospheric circulation associated with MJO's to small-scale SST anomalies, regional-scale SST anomalies, the diurnal cycle, surface waves, upper-ocean mixing, and various other aspects of ocean-atmosphere feedbacks.

OBJECTIVES

The objectives and immediate scientific goals of the proposed research are:

1. *Examine the process by which the SST variability affects the MJO during the DYNAMO using a SCOAR2 regional coupled model.*
2. *Study the MJO predictability and feedback processes on diurnal to intraseasonal time scales;*
3. *Develop a Linear Inverse Model (LIM) for MJO predictions and apply it in retrospective cross-validated forecast mode to the DYNAMO time period.*

APPROACH

We are working as a team to study MJO dynamics and predictability using several models as team members of the ONR DRI associated with the DYNAMO experiment. This is a fundamentally collaborative proposal that involves close collaboration with Dr. Arthur J. Miller of the Scripps Institution of Oceanography. The results presented here include collaborative work involving both Seo and Miller plus former SIO student, Dr. Nick Cavanaugh, because we have discussed, instigated and synthesized each other's research activities and results by keeping in close contact via email and by meeting at various conferences during the past year.

The primary questions we are addressing are:

1) How does the SST variability on diurnal time-scales affect the initiation and intensity of the MJOs in the central Indian Ocean?

This is addressed by conducting a series of SCOAR2 regional coupled model simulations with varied coupling frequencies to suppress the diurnal variations in SST. The warming and moistening during the suppressed phase of the MJO2 and the timing and intensity of the MJO2 convection are interpreted as the impact of the diurnal cycle of SST in the MJO.

2) What are the consequences on the predictive skill of the MJOs DYNAMO by the SST conditions?

This question is addressed by comparing the diurnally coupled SCOAR model simulation for DYNAMO region with two complementary atmosphere-only simulations with modified SST conditions. One WRF simulation is forced with the persistent initial SST, lacking enhanced pre-convection warming and moistening, while the other with prescribed daily-mean SST from the coupled run. The timing and intensity of the MJO2 during in November during DYNAMO are targeted to evaluate the changes in predictability skill due to SST conditions.

3) How much predictive skill for MJO evolution can be obtained using a Linear Inverse Model as a statistical forecasting tool?

Multiple studies have suggested that the MJO may provide an avenue for predictability beyond the traditional 2-week limit MJO hindcast skill studies utilizing high-dimensional numerical models have increased in recent years. Comparatively, there are relatively few statistical forecasts relevant to the MJO. The Linear Inverse Model (LIM, Penland and Magorian 1993) constitutes the least complex form of a reduced stochastic-dynamic climate model (Majda et al. 2009) and has been constructed for atmospheric diagnostics and prediction in several studies (e.g., Winkler et al. 2001, Newman et al. 2003) and coupled atmosphere-ocean modeling (Newman et al. 2009). The models in these studies have comparable predictive capacity to global circulation models for short-term predictions (intraseasonal and shorter), even though they have far fewer degrees of freedom.

TASK COMPLETED

Since the start of this current award in spring, 2013, we have contributed to the following subset of accomplishments of the multi-institutional team:

a. Run SCOAR2 (WRF-ROMS) in downscaling mode for the 2nd MJO event during the DYNAMO period (led by Seo, WHOI, with Miller, SIO)

b. Analyzed SCOAR2 for several years to determine how well MJO's are simulated (led by Seo, SIO, with Miller, SIO)

c. Testing sensitivity to ocean-atmosphere coupling time step (1hr to 1day) for SCOAR2 (led by Seo, WHOI, with Miller, SIO)

d. Developed Linear Inverse Model LIM of MJO predictability (led Cavanaugh and Miller, SIO, with Seo, WHOI)

e. Tested LIM skill in retrospective forecast model for DYNAMO time period (led by Cavanaugh and Miller, SIO, with Seo, WHOI)

f. Attended ONR PI meetings associated with the DYNAMO experiment (Seo, WHOI and Miller, SIO)

RESULTS

The following summarizes our most recent important results during the first year of collaborative research under this research project.

The second version of the Scripps Coupled Ocean-Atmosphere Regional Model (SCOAR2) has been developed and extensively tested for the DYNAMO period with particular emphasis on the

role of the diurnal cycles in the upper ocean and the atmospheric convection. SCOAR2 is configured as the tropical channel model for improved depiction of circumglobal tropical atmospheric circulation (Figure 1). To better capture the thin (~3 meters) diurnal warm layer during DYNAMO, large number of vertical layers is allocated in the upper ocean to allow 4-5 layers in the upper 1-meter and 33 layers in the upper 55 meters. WRF and ROMS share the identical grids and horizontal resolution (40 km). A series of 5-member ensemble simulations has been carried out for the 30-day period from Nov. 14 – Dec. 13 2011 covering the suppressed and the active phase of the second MJO event (hereafter MJO2). Each ensemble run employs different coupling frequencies (CF) ranging from 1-hour (CF1), 3-hours (CF3), 6-hours (CF6), and up to 24 hours (CF24) to explicitly test the effect of resolving diurnal cycle in MJO simulation.

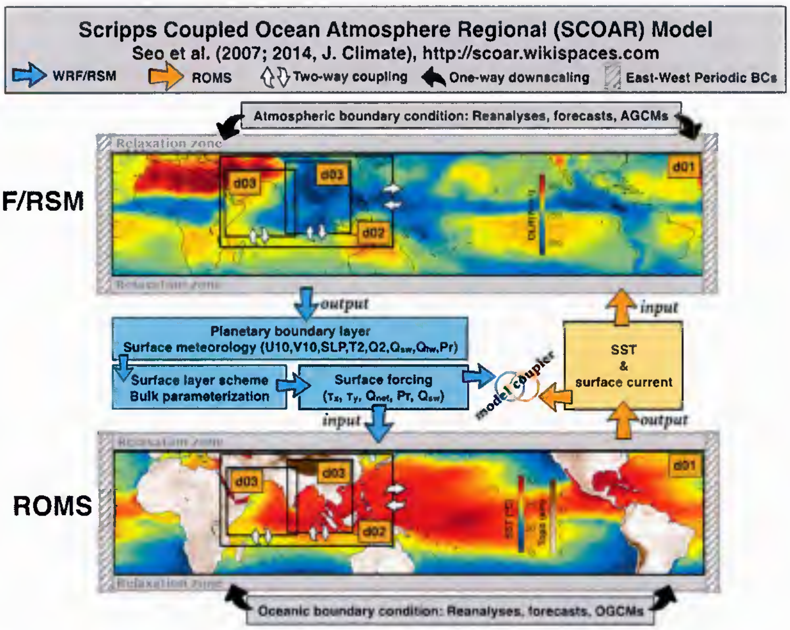

Figure 1. A schematic representation of the SCOAR2 developed for ONR Littoral Air-Sea Processes (LASP) DRI for the DYNAMO.

a. Simulated MJO2 rainfall and sensitivity to CF

Figures 2a-b compare the time-longitude diagrams of observed daily-mean precipitation anomalies (shading) from the TRMM precipitation estimates, overlaid with 850 hPa zonal wind anomaly. In the observations, the MJO2 event is identified as the two intense precipitation episodes with the maximum of 2.3 mmhr^{-1} at 80°E on November 24, which propagated eastward at 8 ms^{-1} (magenta lines) as convectively coupled Kelvin waves. The zonal wind anomalies are in quadrature with the precipitation anomaly by about 5-7 days. Figure 1b shows the eastward propagating precipitation and wind anomalies from CF1 that qualitatively resemble the observations. CF1 shows the strong precipitation maximum at 80°E around November 24-26 which propagated westward as a developing tropical cyclone. Figure 2c shows the diagnostics of the simulated MJO as measured by the Real-time Multivariate MJO (RMM) Index (Wheeler and Hendon, 2004). The trajectories of the observed (black) and simulated (CF1, red) MJO2 in the phase space exhibits a comparable eastward propagating feature, both originating from the Western Hemisphere (Phase 8) and reaching the Maritime Continent (Phase 5). However, the amplitudes of the simulated RMM index (normalized by one standard deviation) and the phase suggest that the simulated MJO is relatively weaker and faster than the observed one. Despite some discrepancy, the local and global characteristics of the simulated MJO reasonably resemble those from the observations

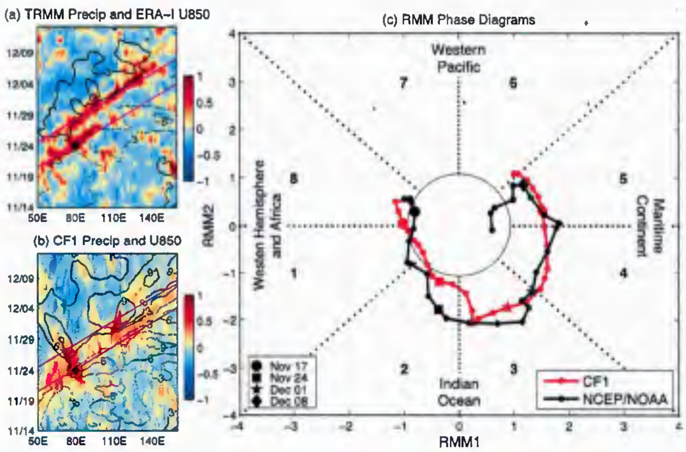

Figure 2. (a) Time–latitude diagrams of the precipitation anomaly from the TRMM (shading, mmh^{-1}) and the 850-hPa zonal wind (U850; contour interval (CI) $=3ms^{-1}$) from the NCEP/NCAR. Two magenta diagonal lines denote the 8 m s^{-1} phase lines. (b) As in (a), but from CF1. (c) RMM phase-space plot for the observations (black) and CF1 (red) for the period from 14 Nov to 13 Dec 2011.

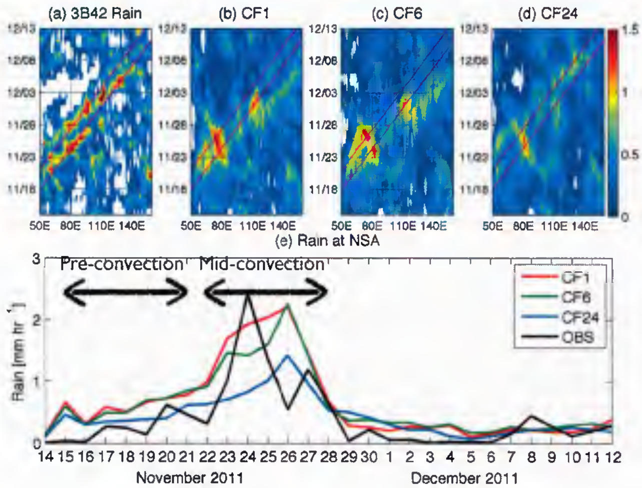

Figure 3. Time-longitude diagrams of rainfall (mm hr^{-1}) over 10°S-10°N from (a) TRMM 3B42, (b) SCOAR2 CF1, (c) CF6, and (d) CF24. (e) Daily precipitation over the DYNAMO domain (73.15-80.5°E and 0.69°S to 6.91°N). The straight diagonal lines, identical in (a)-(d), denote the eastward propagating speed of 8 ms^{-1} beginning at the onset of rainfall event from (a)

b. Upper ocean warming and tropospheric moistening

The upper ocean prior to MJO2 is characterized by strong warming and enhanced diurnal cycle. Figure 4a-c compares the evolution of the upper-ocean temperature anomalies in the DYNAMO domain along with the hourly time-series of anomalous zonal wind at 10 m (U10, blue) and downward shortwave radiation (SWD, red). In all cases, the suppressed phase is characterized by a weak easterly anomaly and a positive SWD anomaly, leading to warming of the upper ocean with sharp diurnal thermocline and shoaled turbulent boundary layer (TBL, gray line). The thickness of the diurnal warm layer, as inferred from the daytime TBL depth, is less than 2 m in CF1 but gets deeper as the CF increases (3 m in CF6 and 7 m in CF24). The pronounced upper-ocean warming anomaly (>0.3°C) below the TBL, reaching >20 m depth in CF1 and evidently less so in CF6 and CF24, is due to the penetration of shortwave radiation flux through the TBL. The thin and warm daytime TBL is deepened at night due to surface radiative cooling and enhanced turbulent mixing in the upper ocean. Clearly, the upper-ocean warming during the suppressed phase is more pronounced and reaches deeper in CF1 than those in CF6 and CF24. The diurnal cycle in the upper ocean temperature is also strongest in CF1. This difference is further illustrated in Figure 4d,e,f, which compare the time-mean profiles of the upper-ocean temperature during the suppressed phase. Error bars represent the respective intra-diurnal standard deviation. The enhanced diurnal variability in the upper 5 m is stronger in CF1 than CF6. The time-mean of both the SST and the top 5-m temperature are higher during this period in CF1, as are the diurnal variations in comparison to that in CF6 and CF24. The greater range of diurnal variation in the upper ocean temperature and SST thus helps the sea surface reach a higher daytime temperature in CF1.

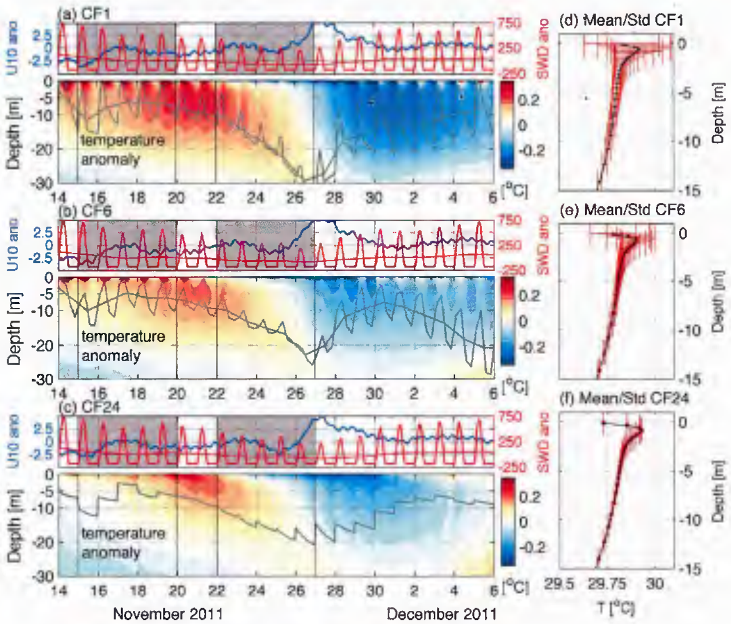

Figure 4. (Left) Time-depth diagrams of the upper ocean temperature anomalies (shading, °C) in the DYNAMO domain from (a) CF1, (b) CF6 and (c) CF24, overlaid with the respective depth of TBL (m, gray contours). Blue and red lines in each panel denote the anomalous 10-m zonal wind (U10, ms^{-1}) and the downward shortwave radiation at the surface (SWD, Wm^{-2}), respectively. (Right) The mean upper ocean temperature profiles are overlaid with ±1 intra-diurnal standard deviation (STD) for the suppressed phase of MJO2 (November 14-21).

c. Impact on the MJO convection

Figure 5 a-c show the depth-time diagrams of the atmospheric specific humidity (q) anomalies over the northern DYNAMO region from the ERA-Interim and two model runs, CF1 and CF24. In both reanalysis and the model, pre-convection period is dominated by the drying of the atmosphere. A gradual moistening is seen from Nov. 20, which then peaks on Nov. 24-26 during the active phase. The anomalous moistening appears to be stronger in CF1 than CF6 (not shown), and than CF24. Mean vertical distribution of specific humidity during the pre- (Figure 5e) and mid-convection (Figure 5f) periods suggests that the air column is moister with more frequent coupling.

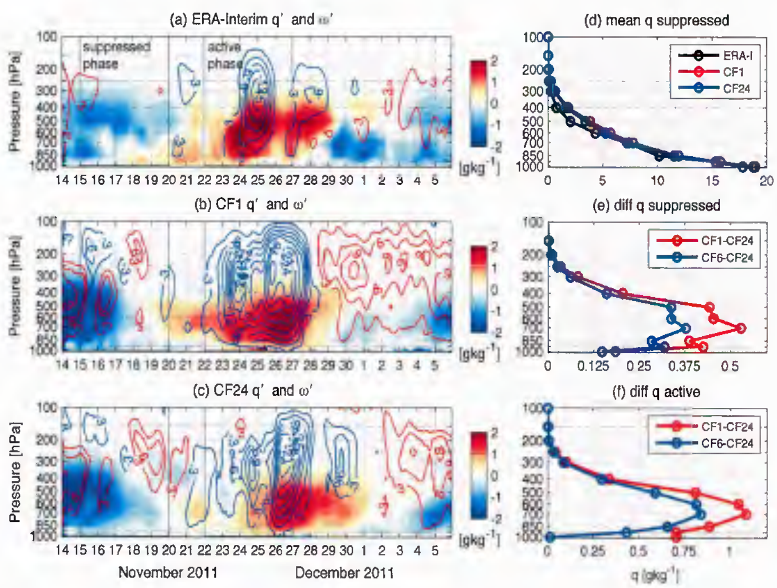

Figure 5 Pressure-time cross-sections of the anomalous specific humidity (q', gkg^{-1}) in the DYNAMO domain from (a) the ERA-Interim, (b) CF1, and (c) CF24. Contours denote the pressure velocity anomaly (ω', $hPahr^{-1}$, CI=10) with the blue (red) representing the ascending (descending) motion. (d) shows the time-mean specific humidity profiles during the suppressed phase of MJO2. The differences in the mean specific humidity are shown for (e) the suppressed and (f) the active phases.

d. Moist Static Energy (MSE) budget analysis

The column-integrated MSE budget analysis has been carried out to elucidate the process that relates the diurnal cycle to the convection intensity. Figure 6a compares the individual MSE budget terms from different CF experiments during the pre-convection period.

$$\underbrace{\langle m_t \rangle}_{\textit{tendency}} = \underbrace{-\langle v_h \cdot \nabla m \rangle}_{\substack{\textit{horizontal} \\ \textit{advection}}} \underbrace{-\langle \omega m_p \rangle}_{\substack{\textit{vertical} \\ \textit{advection}}} + \underbrace{\left(LH + SH \right)}_{\substack{\textit{latent+sensible} \\ \textit{flux}}} + \underbrace{\langle LW + SW \rangle}_{\substack{\textit{long+shortwave} \\ \textit{flux}}}$$

The result clearly illustrates that more frequent coupling leads to greater MSE import to the air column via turbulent heat flux (LH dominant). LH is the only significant source term that accounts for a more expedited rate of MSE recharge with higher coupling frequency. During the active phase of MJO (Figure 6b), vertical advection discharges the MSE via deep convection and precipitation, which also appears to show some correspondence to the coupling frequency. Turbulent and radiative heat fluxes continue to be the source terms of MSE during this phase.

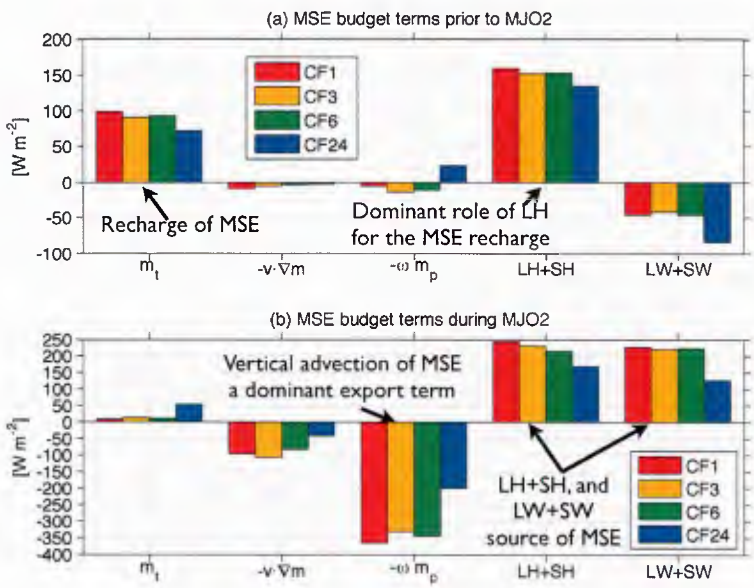

Figure 6. Column integrated MSE budget terms, color-coded to represent different coupling frequencies, for (a) prior to and (b) during the MJO2 event.

e. Summary

By using a set of SCOAR model experiments with varying CFs, we have identified an important role that the diurnal cycle plays during the suppressed and the active phases of MJO2 during DYNAMO. The budget analysis suggests that during the suppressed phase, the warmer SST, achieved by stronger diurnal cycle, allows greater release of latent heat to the atmosphere. This, in turn, leads to a more rapid recharge of column-integrated MSE during the suppressed phase, which then triggers a more intensified convection and precipitation during the active phase. As more frequent coupling results in higher SST and stronger precipitation during DYNAMO, our result demonstrates robust sensitivity of MJO to SST via diurnal cycle on a local scale.

IMPACT FOR SCIENCE

Better understanding of the role ocean and the air-sea interaction in the equatorial Indian Ocean will improve the extended-range (1 week to 1 month) forecasts of MJO for practical use by the Navy. The study stresses the importance of the high-frequency (diurnal) variability in SST and air-sea flux, which have rectified effects on intraseasonal variations in SST and atmospheric convection. Therefore, the results have important implications pertaining to questions on what atmospheric convection and SST feedback processes must be included in the model, how strongly oceanic and atmospheric boundary conditions influence the skill of regional MJO forecasts, and what upper-ocean conditions need to be observed to best execute these practical forecasts.

RELATIONSHIP TO OTHER PROGRAMS

We successfully collaborated with other DRI MJO modelers (e.g., S. Chen, NRL; C. Zhang and M. Ulate, Miami, T. Jensen, Stennis. D. Waliser, JPL, R. Murtugudde, UMd) for comparing simulations in the DYNAMO and YOTC frameworks. We also continue to discuss our research results with Dr. Mark Swenson, Chief Scientist, FNMOC, to determine how effort might eventually be used to improve forecasting of MJO activity for practical use by the Navy. As COAMPS are coupled to the NCOM in real-time mode, our results will provide a comparison to COAMPS skill levels and help point the way in dealing with various regional modeling limitations as well. Extended-range dynamical forecasts in regions influenced by MJO are based on a dynamical process that has potentially useful skill levels. These forecasts are expected to be better than climatology and can contribute to establishing a smart climatology for these regions during times of MJO excitation. This forecast information can then be used in practical Naval operations planning.

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